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HTGR

EXPERIMENTAL PLAN FOR
IRRADIATION EXPERIMENT HRB-21

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EXPERIMENTAL PLAN FOR IRRADIATION EXPERIMENT HRB-21

D. T. Goodin,[*] M. J. Kania, and B. W. Patton

ABSTRACT

Irradiation experiment HRB-21 is the first in a series of test capsules that are designed to provide a fuel-performance data base to be used for the validation of modular high-temperature gas-cooled reactor (MHTGR) coated-particle fuel performance models under MHTGR normal operating conditions and specific licensing basis events. Capsule HRB-21 will contain an advanced TRISO-P UCO/ThO_2-coated-particle fuel system with demonstrated low defective-particle fraction ($\leq 5 \times 10^{-5}$) and a heavy metal-contamination fraction ($\leq 1 \times 10^{-5}$) that meets MHTGR quality specifications. The coated particles and fuel compacts were fabricated in laboratory-scale facilities using MHTGR reference procedures at General Atomics (GA). Nearly 150,000 fissile and fertile particles will be irradiated in capsule HRB-21 at a mean volumetric fuel temperature of 975°C and will achieve a peak fissile burnup of 26% fissions per initial metal atom (FIMA) while accumulating a fast neutron fluence of about 4.5×10^{25} neutrons/m^2.

This experiment is a cooperative effort between the U.S. Department of Energy (DOE) and the Japan Atomic Energy Research Institute (JAERI). The participants are the Oak Ridge National Laboratory (ORNL), GA, and the Tokai Research Establishment. Capsule HRB-21 will contain the U.S. MHTGR fuel specimens, and a companion capsule, HRB-22, will contain the JAERI fuel. The irradiation will take place in the removable beryllium reflector facility of the High Flux Isotope Reactor (HFIR) at ORNL. The performance of the fuel during irradiation will be closely monitored through on-line fission gas release measurements. Detailed postirradiation examination and conduction cooldown simulation testing will be performed on the irradiated fuel compacts from both the HRB-21 and HRB-22 capsules.

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[*]On assignment to Oak Ridge National Laboratory from General Atomics (GA) from October 1, 1986, through September 30, 1987.

1. SCOPE

The HRB-21 irradiation experiment will provide data for the development of the modular high-temperature gas-cooled reactor (MHTGR) in accordance with the MHTGR plant fuel/fission product technology development plan.[1] The test is a cooperative effort of the U.S. Department of Energy (DOE) and the Japan Atomic Energy Research Institute (JAERI). The participants are the Oak Ridge National Laboratory (ORNL), General Atomics (GA), and the Tokai Research Establishment. The HRB-21 capsule will contain 24 fuel compacts of U.S. MHTGR reference quality fuel as well as a variety of encapsulated specimens related to MHTGR fuel performance, fission-product transport, and control materials. A companion capsule designated HRB-22 will contain the JAERI fuel. The HRB-21 capsule will be designed and assembled by ORNL. The fuel compacts, graphite body assemblies, and certain encapsulated specimens will be provided by GA. The irradiation will take place in the removable beryllium reflector area of the High Flux Isotope Reactor (HFIR) at ORNL. The performance of the fuel during irradiation will be monitored by on-line fission gas release measurements. Postirradiation examinations and conduction cooldown simulation testing will be performed with the HRB-21 fuel compacts.

2. OBJECTIVES

The primary objectives of the HRB-21 irradiation experiment are (1) to determine the performance of U.S. (HRB-21) and JAERI (HRB-22) low-enriched-uranium (LEU)-coated-particle fuels under irradiation conditions and (2) to provide samples for postirradiation testing to determine the capability of the particles to meet criteria on failure-fraction limits under accident conditions. The detailed objectives are

1. provide the first in-reactor test of U.S. fuel meeting MHTGR fuel-quality specifications and provide a portion of the data necessary to validate the U.S. reference fuel performance models under normal operating conditions;

2. provide a portion of the samples needed for a series of conduction and cooldown simulation tests designed to update, as necessary, and validate the U.S. reference fuel performance model under conditions called licensing basis events (LBE);

3. provide in-reactor coating failure data for potential revision of the defective-particle performance models;

4. provide irradiated unbonded particles of MHTGR reference quality for (a) direct comparison to defective particle performance in-reactor and (b) selected postirradiation investigations of the structure and performance of reference fuel;

5. provide data on partition coefficients and sorptivity isotherms of Cs, Sr, I, and Ag on MHTGR core materials;

6. provide data on the irradiation performance of both PyC-coated and PyC/SiC-coated particles containing B_4C; and

7. under the auspices of the U.S./Federal Republic of Germany (FRG) umbrella agreement for cooperation in gas-cooled reactor (GCR) development, fuel fission products and graphite subprogram, PWS-FD-25, to provide significant fuel performance data for exchange with the FRG in return for the irradiation of the HFR-B1 capsule.

Experiment HRB-21 will be conducted in accordance with 10CFR50/B requirements for quality assurance as specified in Appendix A of the fuel/fission products technology development plan. Fuel test specimens prepared at GA followed nuclear quality assurance-1 (NQA-1) requirements, and the fuel characterization will be documented in a preirradiation report. The experimental test plan, capsule design and fabrication, irradiation and monitoring, postirradiation tests and examinations, and final documentation will be performed at ORNL in accordance with NQA-1 requirements as documented in the ORNL quality assurance manual.

3. JUSTIFICATION

3.1 REFERENCE FUEL PERFORMANCE

The ceramic fuel of the MHTGR has been studied for nearly three decades, and the fundamental performance characteristics and

fission-product release mechanisms are well understood. The high temperature stability of the MHTGR fuel and the retention of fission products under both normal and off-normal operating conditions have been demonstrated. Validation of the fuel performance models that are used to predict the coated-particle integrity is the primary task remaining to be accomplished.

Although the existing data base is extensive, the MHTGR uses an advanced fuel (TRISO-P UCO/ThO$_2$), and the existing performance models are largely based on data from different fuel systems. In addition, the quality specifications for the MHTGR fuel are more stringent than those in previous plants. Thus, certain assumptions and extrapolations were required so that the existing data base for the MHTGR could be used. In making these assumptions, the uncertainty in the performance descriptions increased. In the case of particle coating failure fraction, this increase in the uncertainty is unacceptably large with regard to compliance with site-boundary dose limits. Reduction of this uncertainty to specified values constitutes validation of the performance models. This is to be accomplished for normal operating conditions by a series of irradiation capsules and postirradiation examinations using reference quality fuel to provide a statistically significant evaluation of the models in comparison with the data.

The HRB-21 capsule will also furnish reference quality irradiated samples for use in conduction cooldown tests (CCT). Although there is an extensive data base from the prior core heatup simulation testing (CHST) program, the CHST program was intended to simulate the conditions for a loss of cooling event in a large [2240 MW(t)] HTGR design. Typically, the CHST simulation transients consisted of heating ramps from 1100 to 2500°C in time periods of about 30 h. In contrast, the MHTGR LBEs involve temperatures of less than 1600°C but for longer times. Thus, the U.S. data base that was developed for the large HTGR is lacking in the intermediate temperature range (1200 to 1600°C) that is of most importance for the MHTGR. Therefore, the present U.S. reference fuel failure model is heavily dependent on the test results of particles manufactured in the FRG. Testing of U.S. fuels is needed to validate the model for use with fuel

manufactured in the United States with MHTGR reference quality specifi-
cations and for use in prismatic cores. This is to be accomplished by a
series of postirradiation heating tests of complete fuel compacts within
graphite bodies (as irradiated) at temperatures in the range of 1400 to
1800°C. These tests will include conditions characteristic of air and
water ingress LBEs for the MHTGR.

3.2 PERFORMANCE OF DEFECTIVE PARTICLES

The term "defective particle" refers to as-fabricated particles that
have at least one intact coating and one or more missing or defective
(e.g., cracked or penetrated) coating layers. The most important example
of a defective particle is one with a missing buffer layer. Such particles
are not expected to release fission products initially during irradiation
but have a higher probability of failure as burnup proceeds because of the
increased internal pressure associated with the lack of void volume
normally provided by the buffer layer. Analytical models based on funda-
mental materials property data are used to calculate the pressure-induced
stress buildup and the consequent probability for failure. This analytical
calculation has an estimated upper 95% confidence limit of ten times the
calculated value. Therefore, specific test data for defective particles
are needed with which to normalize the model calculation.

3.3 SORPTIVITY EXPERIMENTS

To describe the transport through and release from the core of the
MHTGR, data are needed on the sorptivity of fission products on the core
materials. For highly graphitic materials, the sorptivity will change as a
function of neutron fluence, graphite burnoff, and temperature. Data are
lacking for the fission product Ag, and additional data as a function of
burnoff are needed for Cs, Sr, and I. The sorptivity is usually expressed
in terms of the relationship between the partial vapor pressure of the
fission product and the concentration of the metallic fission product in
the sorbent. By use of encapsulated sorptivity specimens in HRB-21, the
partition coefficient (the ratio of the concentration of a selected fission
product in one phase to the concentration in another phase) can be

determined. This partition coefficient method can lead to the determination of the absolute sorption isotherm when evaluated in conjunction with known isotherms. The HRB-21 partition coefficient specimens will provide a necessary comparison of direct in-reactor data to data from out-of-reactor sorptivity experiments.

3.4 B_4C SPECIMENS

Granules of B_4C are utilized in the lumped burnable poison (LBP) and the reserve shutdown control (RSC) pellets of the MHTGR. In the event of an air ingress, uncoated B_4C may undergo preferential oxidation of B_4C to form B_2O_3. The B_2O_3 layer forms around each B_4C granule, and then the rate of reaction slows unless the B_2O_3 layer is removed by vaporization. The boiling point for B_2O_3 is 1250°C; thus, the vaporization will be rapid under conduction cooldown conditions as well as at the higher normal operating temperatures. In the event of water ingress, the B_2O_3 reacts with water to form H_3BO_3 (boric acid) which is volatile at temperatures as low as 300°C.

The MHTGR will utilize pyrocarbon or SiC-coated B_4C granules to inhibit oxidation of the LBP and RSC. The selected coating processes and specifications for B_4C must be shown as acceptable during fabrication, irradiation, and postirradiation heating. Encapsulated B_4C particles will be irradiated in HRB-21 to assure the irradiation performance of the LBP and RSC materials.

4. CAPSULE DESIGN AND DESCRIPTION

4.1 GENERAL CAPSULE DESIGN

The HRB-21 irradiation capsule consists of a doubly contained, single purged cell with fuel compacts surrounded by H-451 graphite bodies (Fig. 4.1). The fuel compacts, three per graphite body, are composed of TRISO-P-coated UCO and ThO_2 particles embedded in graphite matrix material. The eight graphite bodies are contained within two Inconel 718 containment tubes (Fig. 4.2) designed to independently withstand 6.9 MPa (1000 psi)
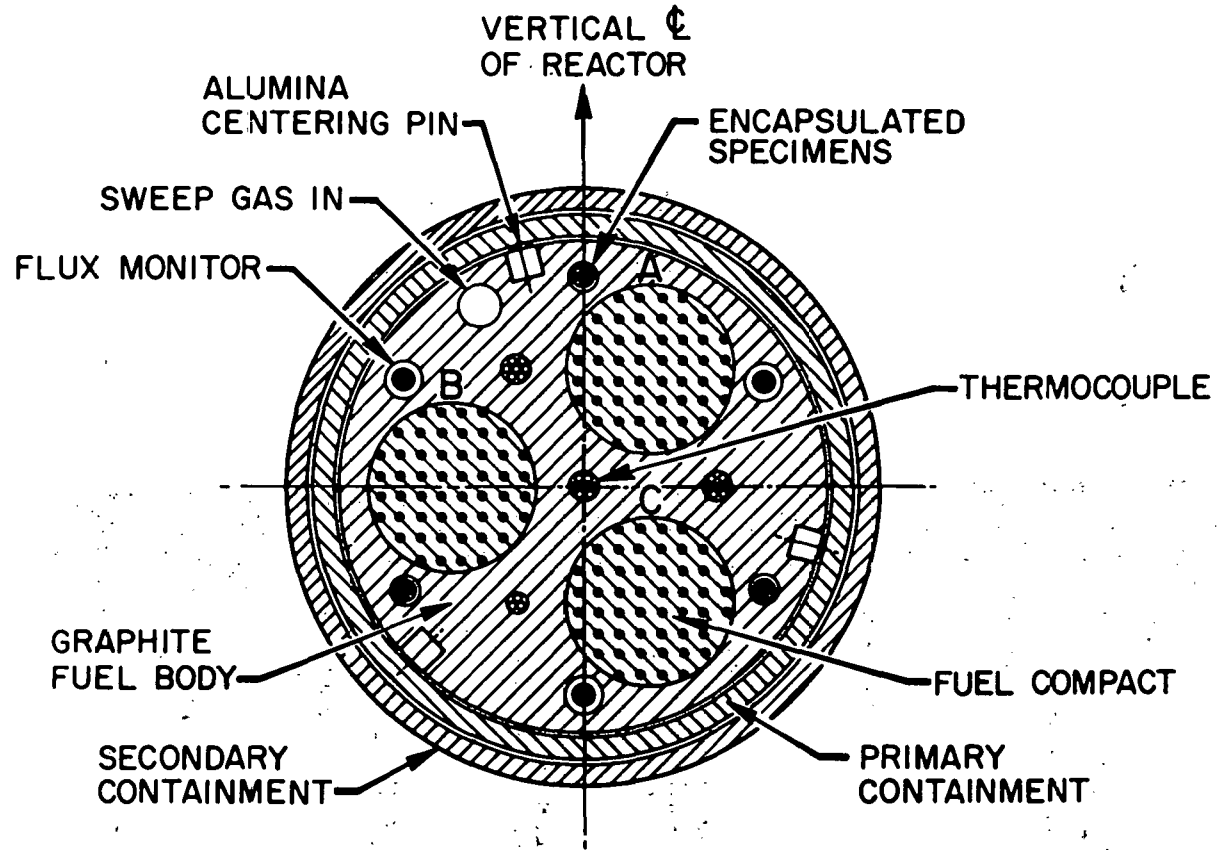
HORIZONTAL SECTION THROUGH CAPSULE HRB-21

Fig. 4.1. Horizontal section through irradiation capsule HRB-21.
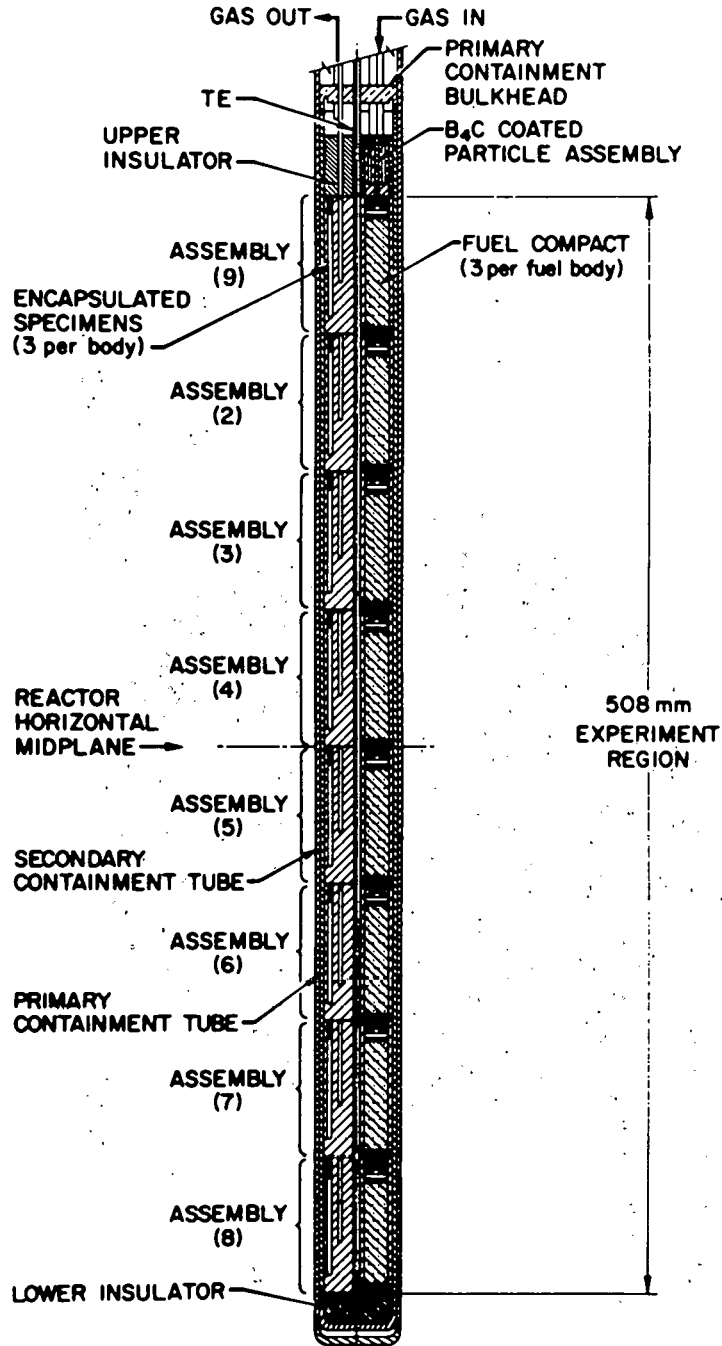
Fig. 4.2. Vertical section through irradiation capsule HRB-21.

inside or outside. During HFIR operation, pure helium at 4.14 MPa
(600 psi) flows between the primary and secondary Inconel containments. A
gas mixture of helium and neon flows between the primary Inconel contain-
ment and the graphite body surface. By varying this gas mixture within the
primary containment, the radial conductance of heat to the surrounding HFIR
cooling water system is controlled, and the operating temperature of the
fuel compacts may be regulated. The entire capsule is fitted with an outer
aluminum liner designed to protect the HFIR beryllium reflector.

The use of Inconel 718 in place of the stainless steel 304 contain-
ment, used in earlier HRB capsules, allows an increase in the linear heat
rate of 49 to 65 kW/m (15 to 20 kW/ft). The increased heat rate allows
irradiation of a larger number of particles. This is especially important
for HRB-21, because large sample sizes are needed to validate the very low
failure-fraction expectations for MHTGR reference quality fuel. The HRB-21
fuel loadings per graphite body are given in Table 4.1.

Table 4.1. Fuel loadings per graphite body

Graphite body number	Total fuel loading (g)				Fissile particles	Fertile particles
	^{235}U	^{238}U	U-total	^{232}Th		
9, 8	0.288	1.173	1.466	7.500	6,700	13,310
2, 7	0.239	0.975	1.214	7.500	5,540	13,310
3, 6	0.176	0.716	0.891	7.500	4,070	13,310
4, 5	0.146	0.594	0.740	7.500	3,380	13,310
		Totals (8 Bodies) =			39,380	106,480

The HRB-21 design thermal analysis was performed with the HEATING6
code,[2] which uses a three-dimensional model in cylindrical coordinates.
The model consists of a graphite holder with insulated boundary conditions
on the top, bottom, and planes of symmetry as illustrated in Fig. 4.3. The
graphite body dimensions for capsule HRB-21 have been determined using a
two-dimensional heat transfer analysis. The radial gaps between the

ORNL--DWG 87--3792 ETD
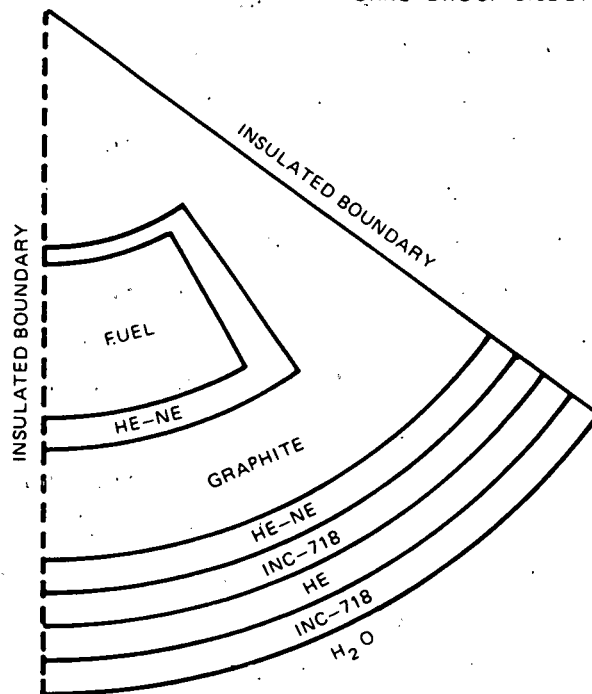
(a)   R-⊝ VIEW
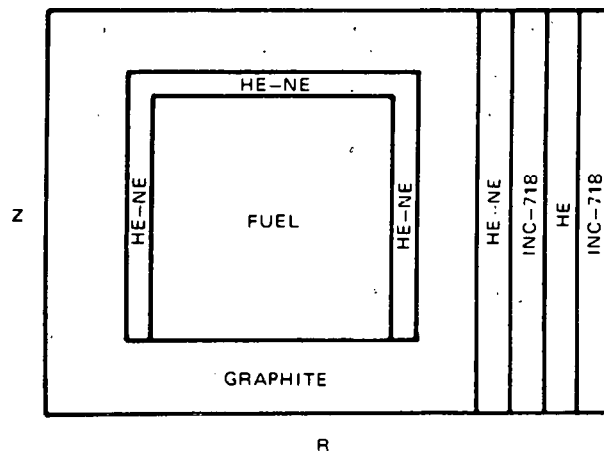
(b)   R-Z VIEW

Fig. 4.3. Cross-section mock-up of irradiation capsule HRB-21 for thermal design calculational purposes: (a) horizontal cross section, R-O view, and (b) longitudinal cross section, R-Z view.

graphite holders and the primary containment wall at operating temperature are as follows:

Graphite fuel body	Radial gap (mm)
9, 8	0.203
2, 7	0.178
3, 6	0.127
4, 5	0.127

All thermocouples in HRB-21 will be placed within the graphite bodies. A total of 24 junctions will be used to monitor the graphite temperatures in four separate thermocouple array assemblies (TCAT).

4.2 DESCRIPTION OF REFERENCE FUEL COMPACTS

The fuel compacts were fabricated and placed within the graphite bodies by GA. Table 4.2 lists the dimensions, weight, and heavy-metal content for each of the fuel compacts used in capsule HBR-21. The reference MHTGR fuel compacts are made by a hot-injection process. This consists of injecting a viscous mixture of binder, binder additive, and graphite filler at temperatures of 150 to 200°C into a closely packed array of coated fuel particles and inert H-451 graphite shim particles contained in a cylindrical mold. The nominal injection pressure has been 6.9 MPa (1000 psi), but was decreased for HBR-21 compact manufacture to reduce particle-to-particle interactions so that the levels of manufacturing-induced coating defects would be decreased.

Petroleum-derived pitch is used as a binder phase, and graphite powder is used for the filler. The as-injected compacts are then heat treated in incremental temperature steps to approximately 1750°C to carbonize the binder phase, drive off volatile gases and impurities, and stabilize the dimensions of the compacts.

The HRB-21 fuel particles are TRISO-P-coated UCO and ThO_2 particles with reference MHTGR dimensions that were produced in the 240-mm development coater in August and September 1986.[3] The coated particles will be

Table 4.2. Capsule HBR-21 fuel compact dimensions and the total heavy-metal loading for 24 compacts to be irradiated in HRB-21

Position from top of capsule	Hole	Outer diameter (mm)			Length (mm)	Weight (g)	U total (g)	Th total (g)
		Top	Middle	Bottom				
1	A	12.45	12.46	12.30	49.13	10.651	0.516	2.355
	B	12.45	12.43	12.27	49.19	10.666	0.516	2.355
	C	12.46	12.45	12.30	49.22	10.667	0.516	2.355
2	A	12.48	12.47	12.37	49.28	10.655	0.402	2.540
	B	12.44	12.47	12.35	49.30	10.676	0.402	2.540
	C	12.45	12.45	12.35	49.26	10.691	0.402	2.540
3	A	12.48	12.46	12.38	49.28	10.581	0.298	2.540
	B	12.46	12.44	12.39	49.29	10.597	0.298	2.540
	C	12.46	12.43	12.33	49.30	10.591	0.298	2.540
4	A	12.46	12.47	12.31	49.32	10.527	0.248	2.500
	B	12.51	12.46	12.32	49.32	10.482	0.248	2.500
	C	12.48	12.46	12.32	49.32	10.505	0.248	2.500
5	A	12.50	12.46	12.33	49.33	10.522	0.248	2.500
	B	12.49	12.45	12.35	49.33	10.511	0.248	2.500
	C	12.49	12.50	12.34	49.32	10.517	0.248	2.500
6	A	12.44	12.46	12.35	49.35	10.589	0.298	2.540
	B	12.46	12.43	12.37	49.32	10.583	0.298	2.540
	C	12.46	12.45	12.35	49.28	10.574	0.298	2.540
7	A	12.46	12.41	12.37	49.33	10.660	0.402	2.540
	B	12.47	12.43	12.35	49.33	10.676	0.402	2.540
	C	12.46	12.43	12.38	49.26	10.703	0.402	2.540
8	A	12.45	12.44	12.32	49.22	10.655	0.516	2.355
	B	12.45	12.45	12.33	49.22	10.646	0.516	2.355
	C	12.45	12.44	12.31	49.16	10.636	0.516	2.355

fabricated into fuel compacts, and companion samples will be tested prior to irradiation to ensure that compacts are consistent with the MHTGR-reference fuel quality specifications with respect to manufacturing defects:

Manufacturing defect missing or defective:	Defect fraction (50% confidence) on mean	Defect fraction (95% confidence) on mean
Buffer	5.0E-05	2.0E-04
IPyC	4.0E-05	1.0E-04
SiC	5.0E-05	1.0E-04
OPyC	1.0E-04	1.0E-03

The compacts will have a heavy-metal contamination of less than
1.0E-05 (50% confidence on mean) and 2.0E-05 (95% confidence on mean).
Initial release to birth (R/B) ratios will be determined for the
unirradiated compacts by a low-flux irradiation in the GA TRIGA reactor.

4.3 DESCRIPTION OF ENCAPSULATED SPECIMENS

Each of the HRB-21 capsule graphite bodies includes three 2.38-mm-diam
(0.094-in.) encapsulated specimen ("piggyback") holes (Fig. 4.1). The
samples to be irradiated will be sealed within niobium tubes 51 mm long by
2.21 mm diam that will be placed in these specimen holes. A schematic of
the general loading arrangement for these specimens is shown in Table 4.3,
and the various sample types are described in the next section.

Table 4.3. HBR-21 encapsulated specimen
test matrix

Graphite holder No.	Fuel compact hole		
	A	B	C
1	S[a]	S	Def(U)[b]
2	Std(U)[c]	Def(U)	Def(U)
3	Std(U)	Def(U)	Def(U)
4	S	S	Def(U)
5	S	S	Def(Th)[d]
6	Std(Th)[e]	Def(Th)	Def(Th)
7	Std(Th)	Def(Th)	Def(Th)
8	S	S	Def(Th)

[a]S = sorptivity specimen.

[b]Def(U) = defective fissile particle (UCO).

[c]Std(U) = standard fissile particle (UCO).

[d]Def(Th) = defective fertile particle (ThO$_2$).

[e]Std(Th) = standard fertile particle (ThO$_2$).

4.3.1 Standard Fuel Particles

'Samples of unbonded fissile and fertile fuel particles selected from the reference fuel fabrication batches will be irradiated in a portion of the holes within the graphite bodies in positions 2, 3, 6, and 7 (Table 4.3). The standard particle irradiation results will be compared with those for defective particles. The standard particles will be available for selected postirradiation analyses and investigations regarding materials performance and fission-product transport.

4.3.2 Defective Fuel Particles

Particles with missing buffer layers are predicted to be the most significant contributors to fission product release during LBEs involving conduction cooldown or water ingress in the MHTGR. Data are needed for potential revision of the bufferless particle-failure model to reduce the uncertainty associated with the present correlation. Whereas separate purged cells in future irradiation capsules will be devoted entirely to investigation of bufferless particle performance, supplementary data can be provided in a timely fashion by the addition of bufferless particle-encapsulated specimens to the HRB-21 experiment.

Bufferless particles are expected to fail earlier than standard particles because of excessive pressure buildup within the particle in the absence of the void volume normally supplied by the buffer layer. The predicted bufferless particle-failure fraction as a function of irradiation time in capsule HRB-21 is shown in Fig. 4.4 for fissile and fertile particles. Given the brittle nature of the primary load-bearing layer of the particle (the SiC), the failure mechanism will likely be a sudden, catastrophic failure of all coating layers. In the case of a bed of unbonded particles, the failure of a single particle is possible, which may result in the failure of an adjacent, highly stressed particle due to load transference. Thus, all bufferless particles will be loaded into individually drilled holes of a POCO graphite crucible to provide separation and shock insulation (Fig. 4.5). This configuration simulates the separation afforded to the bufferless particles by the matrix material of the MHTGR-reference fuel compact. The particles will be protected from contact with

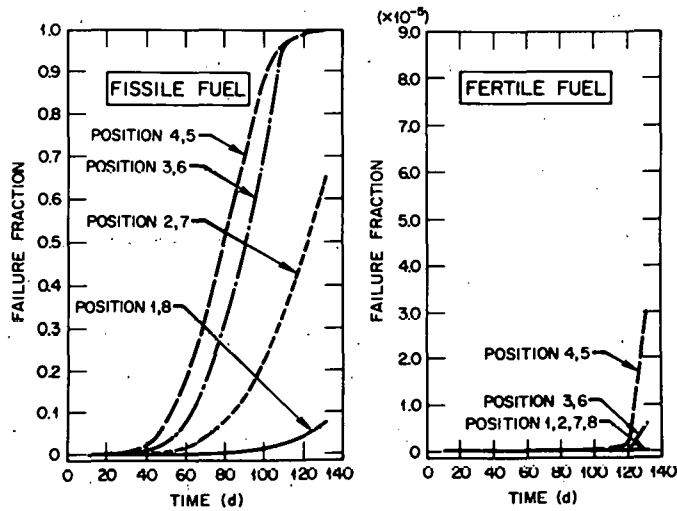Fig. 4.4. Predicted failure fraction
of bufferless particles as a function of
irradiation time in irradiation capsule
HRB-21.

MATERIAL: POCO AXF-5Q-1 GRAPHITE
NOTE: EACH SEALED Nb TUBE SAMPLE CONTAINS
       TWO GRAPHITE LOOSE-PARTICLE HOLDERS, SHOWN ABOVE.
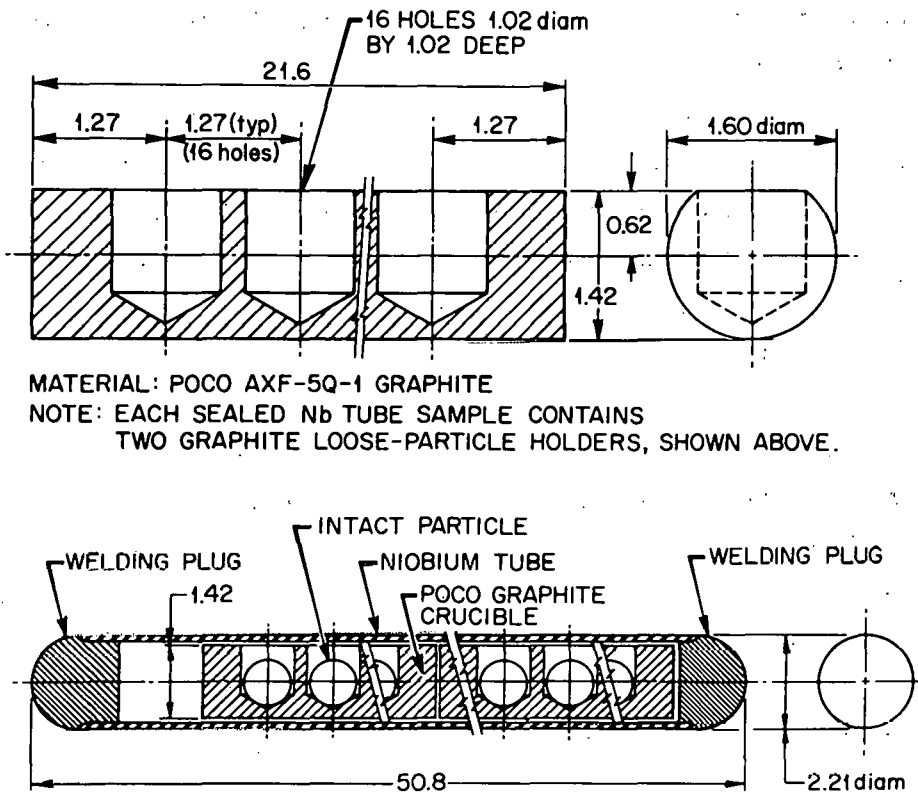
Fig. 4.5. Unbonded particle holder used in capsule
HRB-21 to contain standard and defective coated parti-
cles. All dimensions are in millimeters.

the niobium containment tube by placing a strip of graphite foil in a groove covering the particle holes. As shown in Table 4.3, the defective particle samples will be irradiated in a portion of the holes within each of the graphite bodies.

4.3.3 Sorptivity Specimens

An array of in-reactor sorptivity experiments will allow determination of the partition coefficients of several selected fission products on core materials as a function of temperature, fast neutron fluence, fission-product concentration, and material and extent of material oxidation. The method consists of encapsulating several solid materials in a small niobium tube along with a known quantity of a fission product. The system in-reactor consists of a gaseous phase and several solid phases, and the system undergoes a redistribution of fission products as irradiation damage occurs and approaches a thermodynamic equilibrium. The sorptivity specimen must be designed and constructed so that the gas-phase concentration is sufficiently small such that, upon cooling from the relatively high temperature of the experiment, the gaseous fission products condensing on the solid phases do not appreciably alter the distribution established at the higher temperatures.

The sorptivity specimens are to be placed in the graphite fuel bodies in positions 1, 4, 5, and 8 (Table 4.3). The experimental arrangement of the specimens consists of eight positions, two each in positions 1 and 4 in the upper half of the capsule and two each in positions 5 and 8 in the lower half of the capsule. Positions 1 and 8 and 4 and 5 are symmetric. The sorptivity specimen test matrix is presented in detail in Table 4.4 for each irradiation position. A total of 28 specimens will be irradiated in HRB-21, and 16 specimens will be heated out-of-reactor in laboratory experiments at ORNL. The latter specimens are designated by the "NA" under column heading "Graphite Body Position" in Table 4.4. All of the specimens will be encapsulated in niobium tubes, backfilled with helium, and hermetically sealed prior to positioning in the graphite fuel bodies.

The H-451 graphite and fuel matrix samples will be obtained via coring of larger pieces of graphite and unfueled compacts. The PyC samples are

Table 4.4. Sorptivity specimen test matrix for irradiation capsule HRB-21 including location and identification[a]

Graphite body position	Fluence (10^{25} n/m^2)	Hole A		Hole B	
		Material	Composition	Material	Composition
1	2.2	^{h}GMPS	6Cs + Ag(1)	^hG_oMPS	CS + Ag(1)
		GM	Ag(1)	GM	Ag(2)
		GM	I(1)	GM	I(2)
4	4.9	^{h}GMPS	Cs + Ag(1)	^hG_oMPS	Cs + Ag(1)
		GM	Ag(1)	GM	Ag(2)
		GM	I(1)	GM	I(2)
5	4.9	G_oM	Ag(1)	G_oM	I(1)
		GM	Cs + I(1)	G_oM	Cs + I(1)
		GM	Sr(1)	G_oM	Sr(1)
		GM	Sr(2)	G_oM	Sr(2)
8	2.2	G_oM	Ag(1)	G_oM	I(1)
		G_oM	Ag(2)	G_oM	I(2)
		GM	Cs + I(1)	G_oM	Cs + I(1)
		GM	Sr(1)	G_oM	Sr(2)
NA	0.0	^{h}GMPS	Cs + Ag(1)	^hG_oMPS	Cs + Ag(1)
		GM	Ag(1)	GM	Ag(2)
		GM	I(1)	GM	I(2)
NA	0.0	G_oM	Ag(1)	G_oM	I(1)
		G_oM	Ag(2)	G_oM	I(2)
		GM	Cs + I(1)	G_oM	Cs + I(1)
		GM	Sr(1)	G_oM	Sr(1)
		GM	Sr(2)	G_oM	Sr(2)

[a]G = graphite cylinder

M = matrix cylinder

P = standard inert particle

S = OPyC denuded inert particle

^{h}G = graphite hollow cylinder

G_o = oxidized graphite (1 wt % burnoff)

X(i) = fission product X at concentration level i.

inert fuel particles, and the SiC samples are TRISO-P-coated inert parti-
cles with their BISO-coated outer PyC coating removed. The fission
products are added to the graphite or matrix material by soaking it in a
solution of the desired fission products, drying, and then heating the
material to drive off the volatile components of the solution. The samples
are sealed in a niobium capsule under a helium environment at 1 atm.

4.3.4 Coated B_4C Specimens

The coated B_4C particles consist of two types. One batch of particles
is PyC coated, and the other is coated with PyC/SiC coating. The particles
will be placed within 5.1-mm-OD POCO graphite crucibles with a length of
28 mm (Fig. 4.6). Each graphite crucible will be loaded with approximately
170 particles of each B_4C particle type. Six of the B_4C crucibles will
then be located in the upper insulator of the HRB-21 capsule. This
insulator is located just above the top graphite fuel body-fuel position
and is approximately 260 mm above the HFIR horizontal midplane.
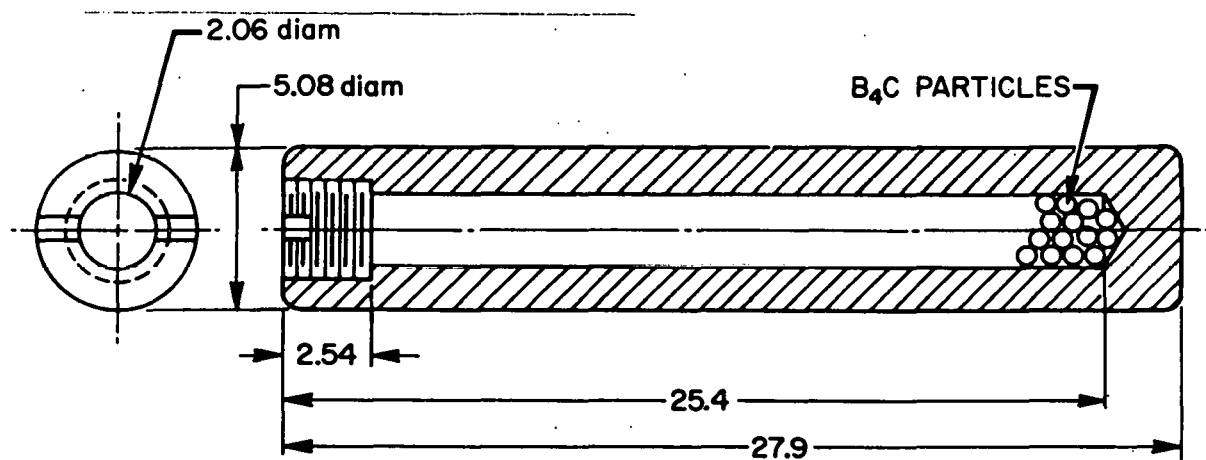
ORNL-DWG 88-11614

NOTE:
* ALL DIMENSIONS ARE IN MILLIMETERS
* MATERIAL IS POCO GRAPHITE

Fig. 4.6. Particle holder for the evaluation of lumped burnable poi-
son (LBP) and the reserve shutdown control (RSC)-coated B_4C particles.

4.3.5 Dosimetry and Flux Monitors

Appropriate dosimetry will be placed in each graphite body of HRB-21. The dosimetry materials will be such that the total fluence, the thermal fluence, and the fast neutron fluence can be determined by postirradiation analysis of the dosimetry.

5. IRRADIATION CONDITIONS

5.1 IRRADIATION TEMPERATURE

Capsule HRB-21 has a target volumetric fuel average temperature of 975°C. The graphite body radial gaps have been specified to maintain this temperature as uniformly as possible over the length of the capsule. Fuel compact temperatures will be inferred from the graphite thermocouple temperature data and the preirradiation design thermal analysis. In-reactor temperature control will be maintained by adjusting the neon and helium concentrations in the sweep gas. After irradiation and completion of the fuel/graphite metrology, a detailed thermal analysis will be performed to obtain in-reactor fuel compact temperatures.

A total of 24 thermocouples will be placed in the graphite fuel bodies to monitor temperatures during the irradiation. Within each fuel body, three thermocouple junctions will be located on an axial plane as close as possible to the midpoint of each 50-mm-long fuel compact. The thermocouple arrangement is shown in Fig. 5.1. The expected fuel operating temperature uncertainty during irradiation may be as high as ±150°C because of the lack of temperature monitors within the fuel compacts themselves. This uncertainty is expected to be reduced to ±60°C after postirradiation metrology and completion of the detailed thermal analysis. The average graphite operating temperature is expected to be about 650°C.

5.2 FUEL BURNUP

The HRB-21 fuel fissile- and fertile-particle burnup estimates have been made using the CACA-2 fuel depletion code[4] for a six-cycle irradiation

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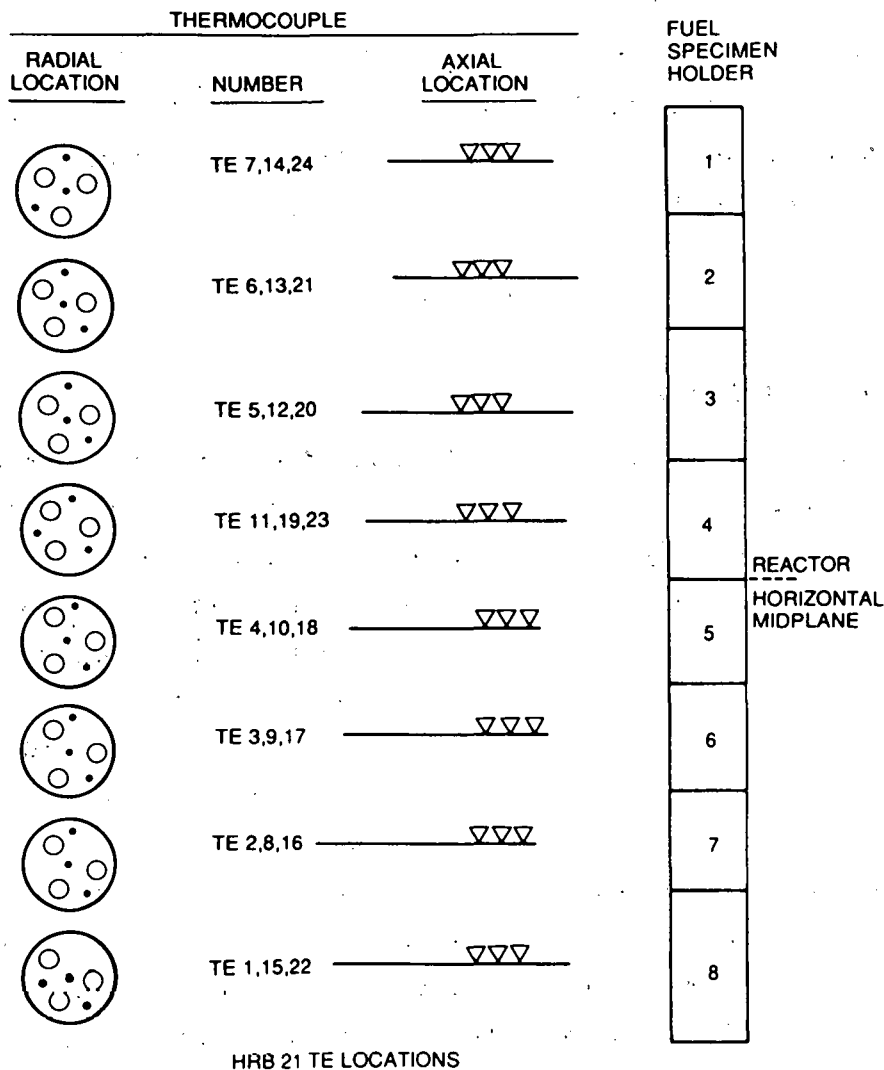
Fig. 5.1. Thermocouple arrangement in irradiation capsule HRB-21.

in the HFIR Removable Beryllium Reflector Irradiation (RB*) facility. The maximum expected end-of-life burnup near the HFIR midplane (positions 4 and 5) is 24.4% FIMA for the fissile fuel and 2.7% for the fertile fuel. The minimum expected end-of life burnup at the graphite body positions 1 and 8 is 15.5% fissile and 0.7% fertile. The expected burnup profiles as a function of irradiation time are shown in Figure 5.2. Calculations of burnup based on dosimetry data and unbonded particle analysis will be performed during HRB-21 postirradiation examinations.

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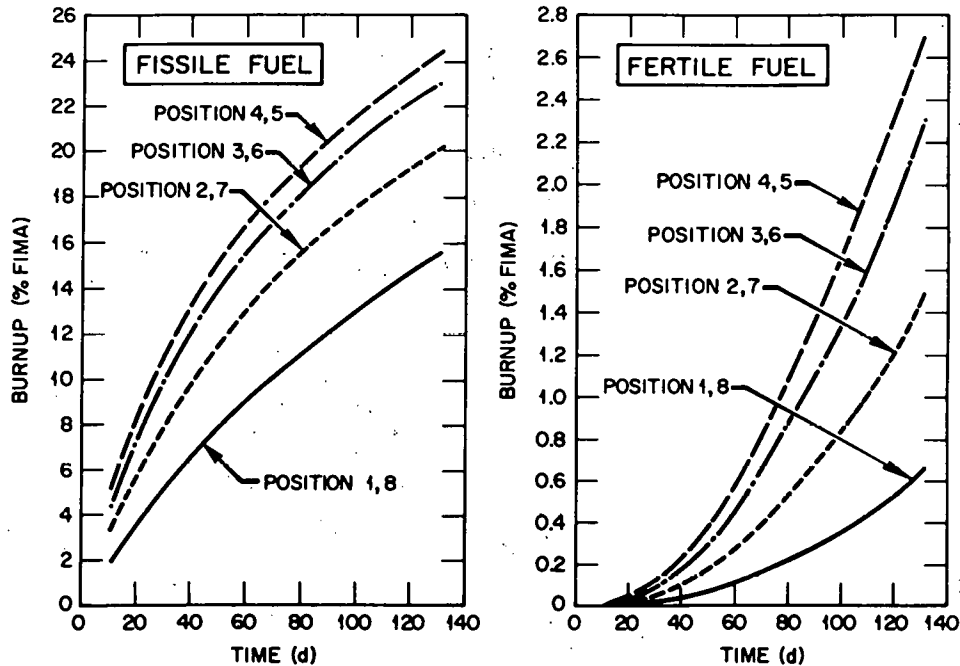
Fig. 5.2. Predicted fissile and fertile particle
burnup profiles in capsule HRB-21.

5.3 FLUENCE

The expected HRB-21 fast fluence exposure values have been calculated
using dosimetry data acquired previously.[5] Because of the modifications of
the RB* facility, the fluence predictions are not known precisely and may
be in error by approximately 10%. Dosimetry located within the HRB-21
graphite bodies will provide measured flux and energy spectrum values. The
predicted fast fluence values as a function of capsule position based on
prior data are shown in Fig. 5.3.

6. POSTIRRADIATION EXAMINATION (PIE)

After completion of the scheduled 6-cycle irradiation in the HFIR,
capsule HRB-21 will be removed from the reactor and allowed to cool in the
pool-side facility for 1 to 3 weeks. The capsule will then be loaded into
a special transportation cask and moved to the High Radiation Level
Examination Laboratory (HRLEL) for disassembly and PIE.

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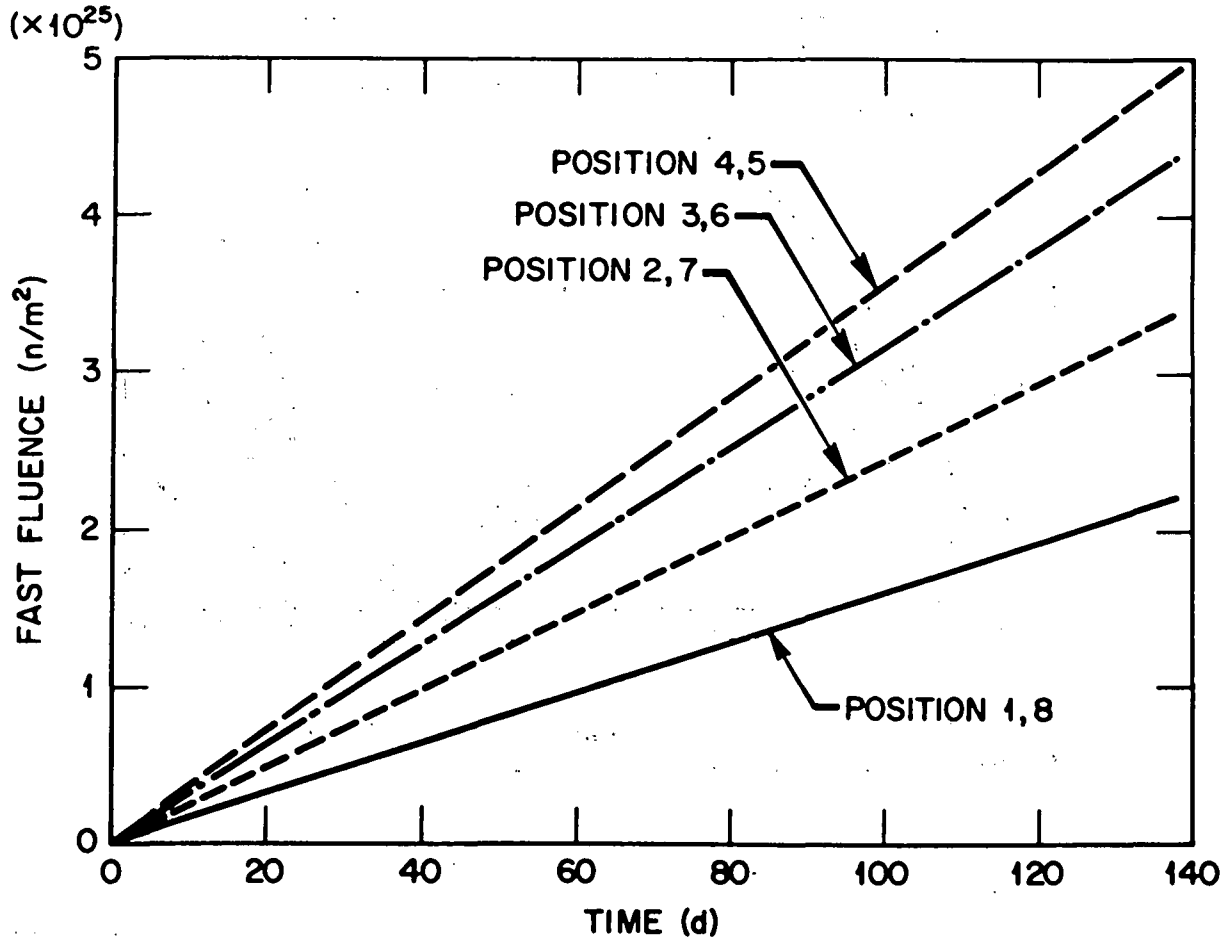
Fig. 5.3. Predicted accumulated fast neutron fluence (E > 29 fJ) in capsule HRB-21.

Capsule HRB-21 disassembly and PIE will be performed according to a well-defined plan that will be available to the HRLEL staff prior to initiation of PIE. This plan will provide detailed disassembly procedures, and a PIE test matrix and PIE procedures to be used for examination of the irradiated fuel, graphite, and piggyback specimens.

The irradiated specimens will be removed from the capsule containments by making circumferential cuts at the top and bottom of the fueled portion of the capsule. (Engineering drawings with indicated cuts will be supplied in the PIE plan.) At this point the thermocouple arrays will be removed

and stored for further analysis if necessary. The circumferential cut surfaces will be deburred, and the carbon insulators and graphite fuel bodies will be removed by pushing them out onto a clean positioning tray. The insulators and graphite bodies will be visually examined and photographed, and any unusual areas will be noted. Dimensional measurements will be determined on the insulators, and graphite bodies at various locations that will permit direct comparison with preirradiation dimensions. These data will be used in the postirradiation thermal analysis. Each fuel body will then be stored in a properly identified individual container for further disassembly and PIE. The primary and secondary containments will also be stored in properly identified containers for further analysis.

For each graphite fuel body, the encapsulated specimens—dosimeters, sorptivity specimens, and unbonded particle specimens—will be extracted by removing the screw caps holding them in place. The sorptivity specimens and dosimetry specimens will be stored in properly identified containers to be examined later by high-resolution gamma spectrometry to determine activation product inventories. The standard and defective unbonded particle specimens will be removed in a similar fashion and stored in properly identified containers. The unbonded particles will be removed from the niobium encapsulation with the container gas content measured upon opening. After removal, the unbonded particles will be subjected to visual and irradiated-microsphere gamma analyzer (IMGA) examinations to establish failure levels.

For a limited number of graphite fuel bodies (tentatively bodies 5, 6, and 8), the irradiated fuel compacts will be unloaded by removing the screw caps holding them in place at the bottom of the body. The compacts will be visually examined and photographed, and any unusual areas will be noted. Diameter and length measurements at several locations will be made along the compact length to establish irradiation-induced shrinkage for use in the postirradiation thermal analysis. After fuel-compact removal, the bonding strength of the upper fuel-closure plugs (cemented in place at time of fabrication) will be measured by a pushout test using a force gage.

The fuel compacts from fuel bodies 5, 6, and 8 will be subjected to detailed examinations to establish the fraction of particles with (a) totally failed coatings and (b) failed SiC but intact outer PyC coatings. A tentative PIE test matrix for these compacts is provided in Table 6.1.

Table 6.1. Tentative PIE test matrix for eight fuel compacts

Compact	TRIGA Activation	Metallography	Total failure	IMGA	TRIGA reactivation	CCT	Post-CCT exam
9						X	X
2					X	X	X
3						X	X
4					X	X	X
5	X	X	X	X			
6	X	X	X	X			
7					X	X	X
8	X	X	X	X			

The integrity of as-irradiated fuel particles heated in the CCT program can be assessed by the initial release profiles measured as the CCT sample are brought to test temperature (prior to high-temperature induced failure). For example, adequately low releases (in agreement with model expectations) during both in-reactor operations and during heatup to 1600°C (and for an expected time thereafter) is a direct demonstration of the retentive capability of the fuel for MHTGR service.

6.1 CONDUCTION COOLDOWN TESTING

A conduction cooldown test facility (CCTF) is being constructed at ORNL to provide simulation of the conditions of MHTGR LBEs and measurement of fuel failure and fission-product release. The majority of the HRB-21 graphite bodies will be subjected to postirradiation heating tests in the CCTF. Since the methods validation program for normal operating conditions

will examine in-reactor performance at temperatures up to 1250°C, the CCTs will emphasize the temperature range of 1400 to 1800°C.

A final allocation of samples within the postirradiation test matrix depends upon HRB-21 in-reactor fuel performance results. A tentative CCT matrix for HRB-21 samples, which assumes in-reactor performance that meets MHTGR release limits, is given in Table 6.2. For planning purposes, the

Table 6.2. Tentative CCT matrix for HRB-21 samples

Test No.	Body No.	Heating temperature (°C)	Average % FIMA		Number of particles	
			Fissile	Fertile	Fissile	Fertile
1	9	1600	15.5	0.7	6,700	13,310
2	2	1400	20.2	1.5	5,540	13,310
3	7	1800	20.2	1.5	5,540	13,310
4	3	1600	23.0	2.3	4,070	13,310
5	4	1600	24.4	2.7	3,380	13,310
Total					25,230	66,550

CCT times are estimated to be 1000 h for tests at temperature of less than or equal to 1600°C and 500 h for tests at a temperature greater than 1600°C. The actual test times will be determined jointly by the test engineer in consultation with the data analyst based on the observed fission product release in each test, the furnace capabilities, and the data needs for model validation purposes.

7. TENTATIVE SCHEDULE

The following tentative schedule for capsule HRB-21 is planned. This schedule is a target schedule subject to HFIR startup and shutdown requirements and interference from other experiments in the HRLEL.

	Completion date
Capsule HRB-21 planning	September 1987
Complete fuel/graphite fabrication	December 1987
Complete capsule assembly	November 1988
Insert HRB-21 in HFIR	July 1989
Remove HRB-21 from HFIR	December 1989
Complete disassembly/metrology	April 1990
Complete thermal analysis	November 1990
Complete postirradiation examination	June 1991
Conduction cooldown tests	September 1991
Complete topical report	February 1992

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